SUSY 2024
Theory meets Experiment

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

The Dark Matter-Baryon Coincidence from Dark Grand Unification

with Shihwen Hor (Tokyo U.) , work in progress

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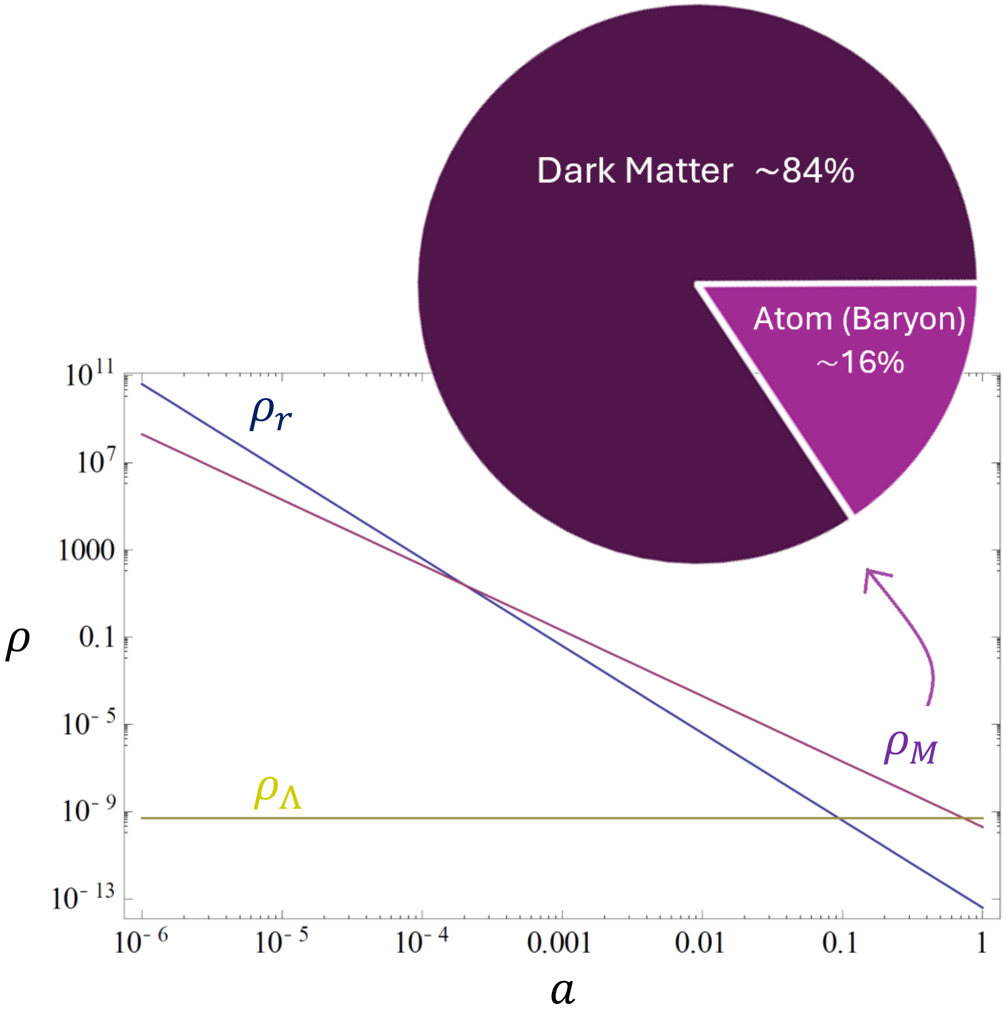
The Dark Matter-Baryon Coincidence



$\Rightarrow$ Why $\rho_D/\rho_B \sim 5$?

For comparison,

$\rho_{\mathrm{proton}} \,/\, \rho_{\mathrm{neutron}} \sim 7$

$\rho_{\mathrm{proton}} \,/\, \rho_{\mathrm{electron}} \sim 1800$

More about the DM-Baryon Coincidence

- For non-relativistic particles, the energy density = number density × mass

$$\rho_D/\rho_B \quad = \quad n_D/n_B \quad \times \quad m_D/m_B \quad = \; 5\,!?$$

from unknown Baryogenesis

from QCD confinement

- For comparison,

$$\rho_p/\rho_n \quad = \quad n_p/n_n \quad \times \quad m_p/m_n \quad = \; 7$$

~7 from BBN

$$\sim 1$$

$$\rho_p/\rho_e \quad = \quad n_p/n_e \quad \times \quad m_p/m_e \quad = \; 1800$$

$$\sim 1 \because U(1)_{EM} \qquad \sim 1800$$

Solutions to the coincidence problem

- There are two types of solutions:

1. $n_D \neq n_B$ & $m_D \neq m_B$: Dynamical solution (see 2310.07777 by A. Hook & D. Brzeminski)
2. $n_D \sim n_B$ & $m_D \sim m_B$: Solutions based on similarity

◆ The first condition $n_D \sim n_B$ has already been discussed in Asymmetric Dark Matter models

◆ Several ideas have been proposed to address the second condition $m_D \sim m_B \sim \Lambda_{\mathrm{QCD}}$

What does Λ_{QCD} depend on?

$$\Lambda_{\mathrm{QCD}} \sim \exp\left(-\frac{2\pi}{b \cdot \alpha}\right) \cdot M_{\mathrm{Planck}} \quad \Rightarrow$$

$\left\{\begin{array}{l} b \text{ is the coefficient of bata function} \\ \alpha \text{ is the coupling strength at } M_{\mathrm{Planck}} \end{array}\right.$

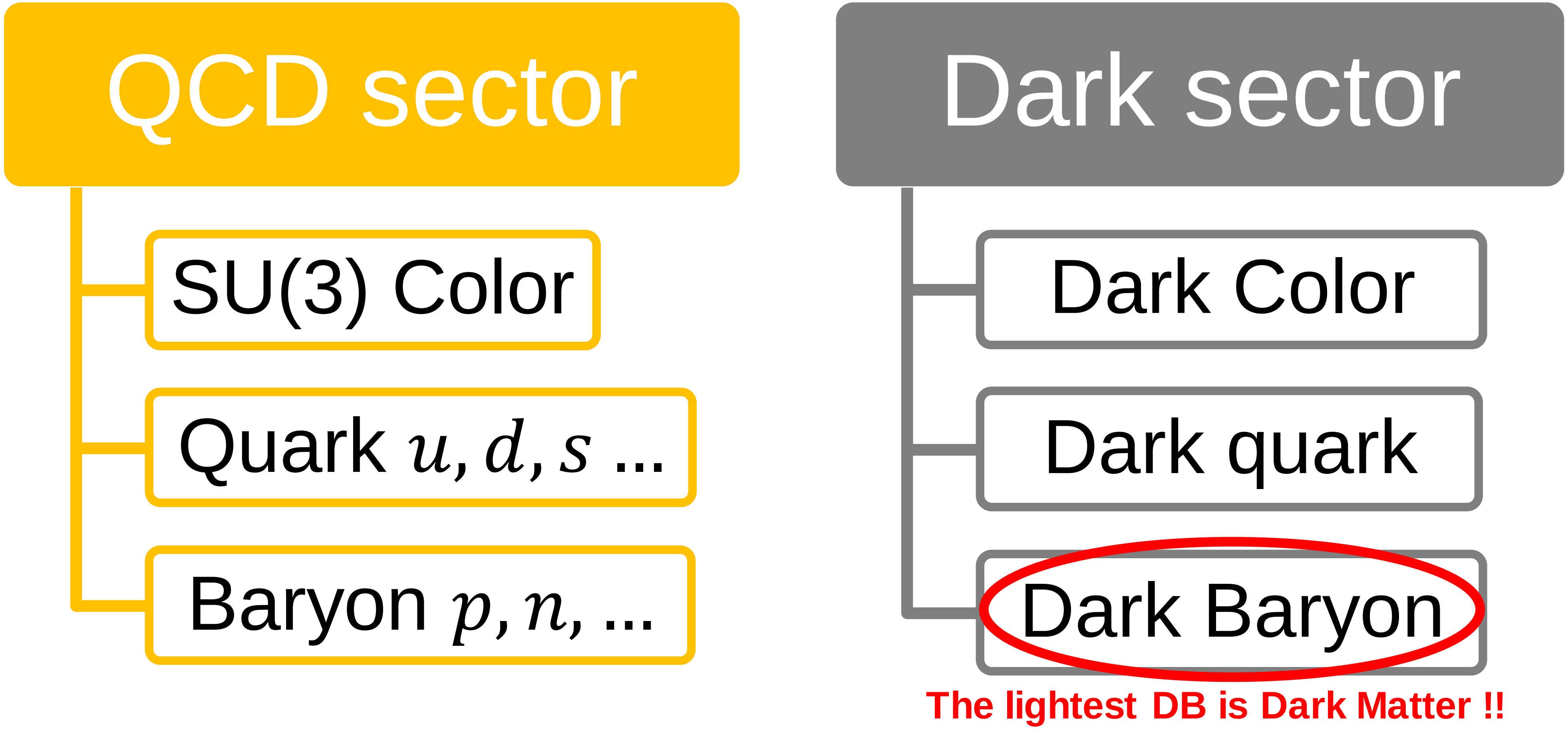
1) Symmetry (ex. Z_2) : $b_D \sim b_B, \;\; \alpha_D \sim \alpha_B$

2) Infrared fixed point : $b_D = b_B = 0$

3) Dark-Color Unification : $\alpha_D \sim \alpha_B$

Dark Sector

- A direct consequence of similarity-based solutions is Dark sector ~ QCD sector



QCD sector

- SU(3) Color
- Quark u, d, s ...
- Baryon $p, n,$ ...

Dark sector

- Dark Color
- Dark quark
- Dark Baryon

The lightest DB is Dark Matter !!

Choice of Dark Color

- The Dark-Color Unification only guarantees $\alpha_{\rm DC} \sim \alpha_{\rm QCD}$ at a high scale. To have $m_D \sim m_B$ (i.e. $\Lambda_{\rm DC} \sim \Lambda_{\rm QCD}$), we still need a little coincidence for $b_{\rm DC} \sim b_{\rm QCD}$
- To achieve this, we consider one-loop beta functions given by

$$\frac{d\,g}{d\ln\mu} = -\frac{1}{16\pi^2}\,b\,g^3 \quad , \text{ where } \quad b = \frac{11}{3}\underline{C_2(G)} - \frac{1}{6}\underline{n_s T(R_s)} - \frac{2}{3}\underline{n_f T(R_f)}$$

$$\textbf{QCD :} \qquad \mathbf{= 3} \qquad \mathbf{= 0} \qquad \mathbf{= 3 \times 4 \times 1/2}$$

- The leading contribution is the $C_2(G)$ term from the gauge bosons. The little coincidence requires the Dark Color group with the same $C_2(G) = 3$ (with $T_f = 1/2$)

$$\Rightarrow \qquad SU(3), \qquad \boldsymbol{Sp(4)}, \qquad SO(8)$$

Fermion content

- Start with the $SU(5)$ GUT, where the SM fermion content is organized as

SM : $$10 = \begin{pmatrix} u^c & q \\ & e^c \end{pmatrix} \; + \; \bar{5} = \begin{pmatrix} d^c \\ \ell \end{pmatrix}$$ for each generation

- Based on this, the extension of gauge group $SU(5+N)$ will automatically include SM singlets

$$A = \begin{pmatrix} \chi_A & \chi_C & \chi_W \\ & u^c & q \\ & & e^c \end{pmatrix} \; + \; \bar{F} = \begin{pmatrix} \chi_F \\ d^c \\ \ell \end{pmatrix} \; + \; N \times \bar{F} = \begin{pmatrix} \psi_F \\ \psi_C \\ \psi_W \end{pmatrix}$$

✓ χ_A, χ_F are ideal dark quark candidate, which should be light (below $\Lambda_{\rm DC}$)

✓ χ_C, χ_W carry both DC and SM charges, which should be heavy

✓ ψ_F, ψ_C, ψ_W are exotic fermions to cancel anomalies, which should be heavy

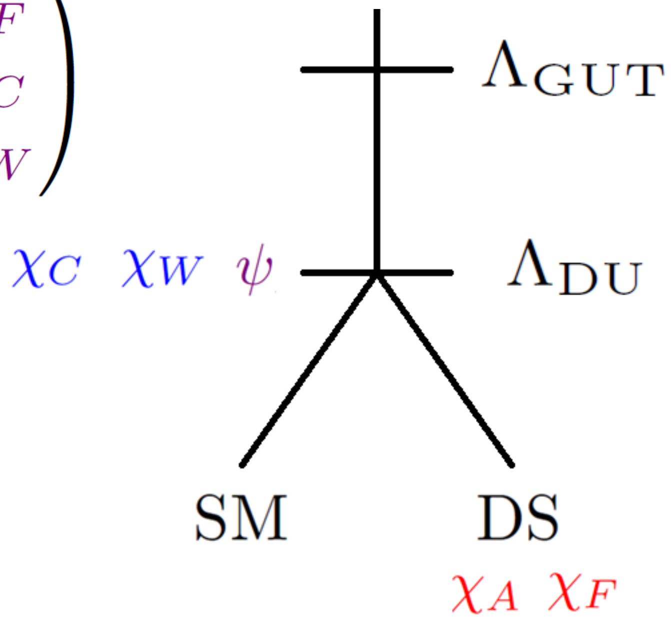
Dark Grand Unification

- By choosing $N = 4$, the DarkGUT group is $SU(9)$ and the desired breaking chain is

$$SU(9) \xrightarrow{\Lambda_{\text{GUT}}} SU(2)_W \times \left[U(1)_X \times SU(7)_{\text{DU}} \xrightarrow{\Lambda_{\text{DU}}} U(1)_Y \times SU(3)_C \times Sp(4)_D \right]$$

with fermion content given by

$$36 = \begin{pmatrix} \chi_A & \chi_C & \chi_W \\ & u^c & q \\ & & e^c \end{pmatrix} + \bar{9} = \begin{pmatrix} \chi_F \\ d^c \\ \ell \end{pmatrix} + 4 \times \bar{9} = \begin{pmatrix} \psi_F \\ \psi_C \\ \psi_W \end{pmatrix}$$



- Scalar content is required to

1. Include the SM Higgs doublet
2. Realize the desired symmetry breaking
3. Give masses to all the new fermions

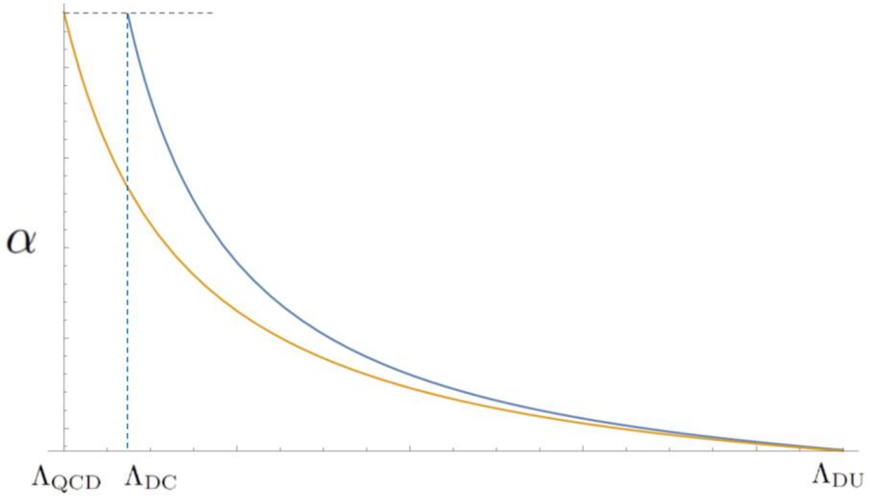
Dark Sector - Dark Color Running

- Below the scale Λ_{DU}, we have the Dark sector = $Sp(4)_D$ with $3\times(\chi_A+\chi_F)$

  and we can derive

$$b_{\mathrm{DC}} = \frac{11}{3}\times 3 - \frac{2}{3}\times 3\times(1\times 1 + 1\times\frac{1}{2}) = 11-3 = 8 \quad > \quad b_{\mathrm{QCD}} = 7$$

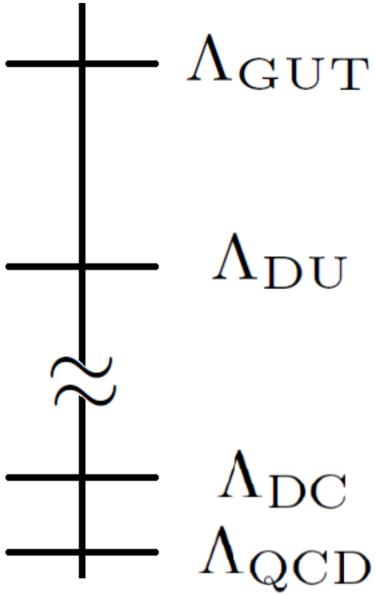
which directly implies that Λ_{DC} & m_D is slightly greater than Λ_{QCD} & m_B



$$\text{With } \Lambda_{\mathrm{DU}} \sim 10^8 \text{ GeV}$$

$$\Longrightarrow \quad \Lambda_{\mathrm{DC}} \sim 5\,\Lambda_{\mathrm{QCD}}$$

$$\xRightarrow{n_D = n_B} \rho_D \sim 5\,\rho_B\,!!$$



Dark Sector – Dark Hadron Spectrum

$Sp(4)_D$ with $3 \times (\chi_A + \chi_F)$

- The hadron spectrum can be derived by Lattice calculations.

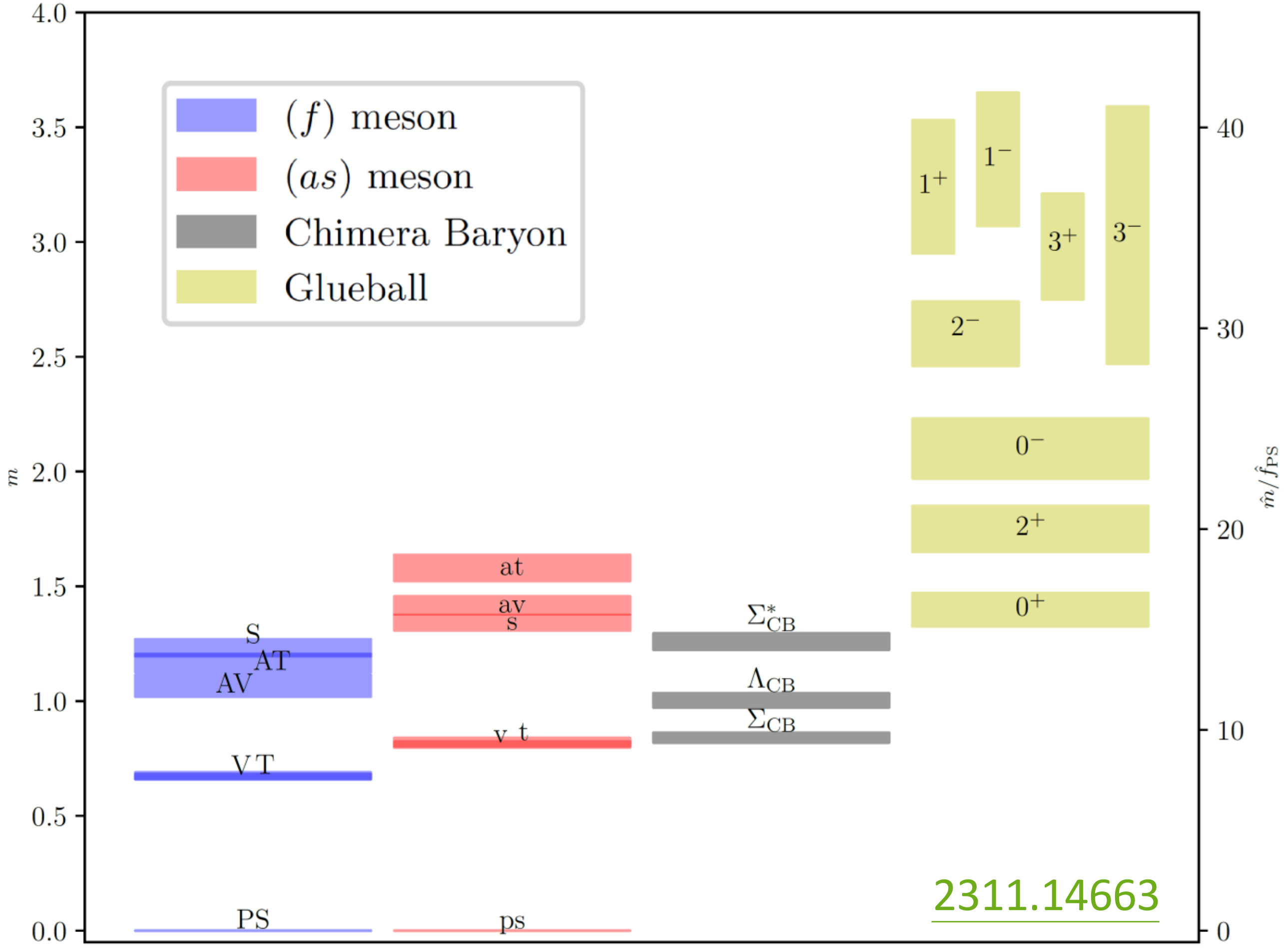


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FIG. 13: Quenched spectrum of the $Sp(4)$ gauge theory in the continuum and massless-hyperquark limit.

Dark Sector – Dark Hadron Spectrum

$Sp(4)_D$ with $3 \times (\chi_A + \chi_F)$

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- The lightest Baryon state ($D = 1$) is the fermionic “Chimera Baryon”.

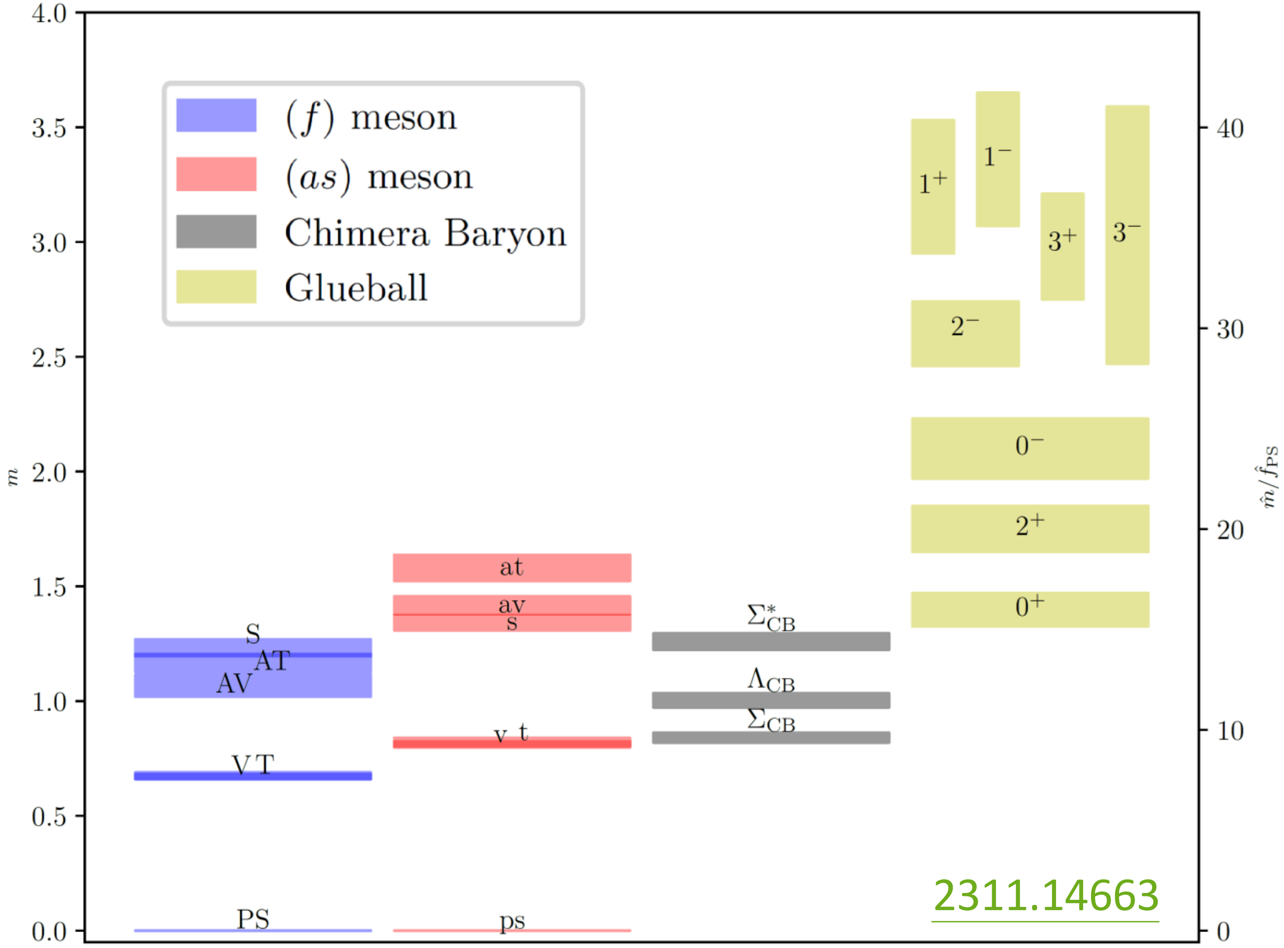

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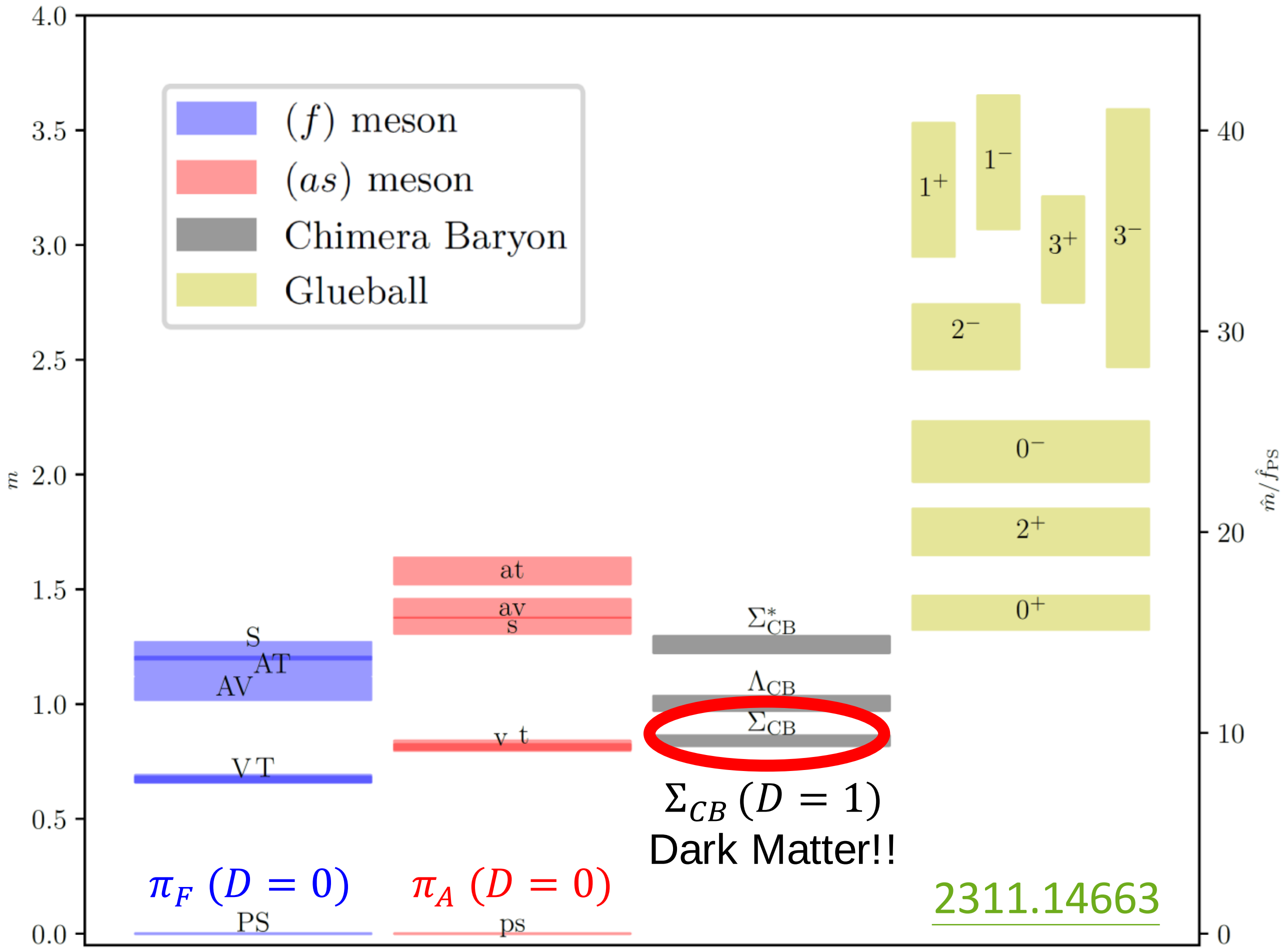
FIG. 13: Quenched spectrum of the $Sp(4)$ gauge theory in the continuum and massless-hyperquark limit.

Dark Sector – Dark Hadron Spectrum

$Sp(4)_D$ with $3 \times (\chi_A + \chi_F)$

- The hadron spectrum can be derived by Lattice calculations.
- The lightest Baryon state ($D = 1$) is the fermionic “Chimera Baryon”.
- The lightest Chimera Baryon is stable and serving as Dark Matter!!
- There are also light pions ($D = 0$), including π_F (by χ_F) and π_A (by χ_A).
- In a realistic model, there are also dark quark masses (massive pions) and flavor (three generations) !!



π_F ($D = 0$)

π_A ($D = 0$)

Σ_{CB} ($D = 1$)
Dark Matter!!

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FIG. 13: Quenched spectrum of the $Sp(4)$ gauge theory in the continuum and massless-hyperquark limit.

Dark Sector

- Comparison between the QCD sector and the Dark sector

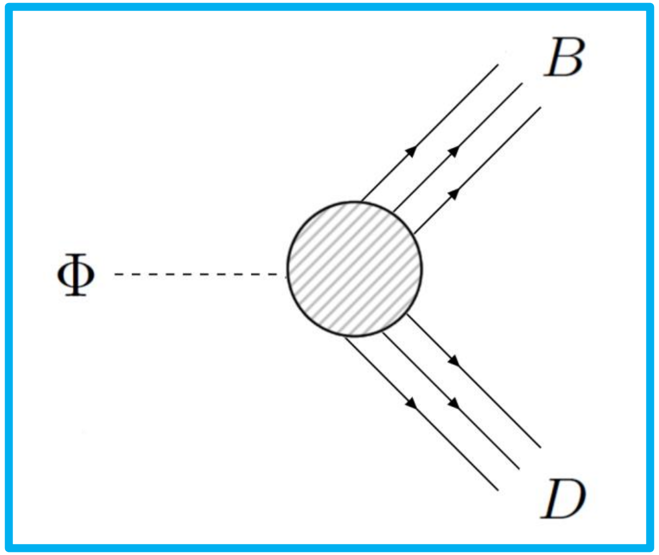
- QCD sector
  - SU(3) Color
  - Quark u, d, s ...
  - Baryon $p, n,$ ...
- Dark sector
  - Sp(4) Dark Color
  - Dark quark $3 \times (\chi_A, \chi_F)$
  - Dark Baryon Σ_{CB} Λ_{CB} , ...

The lightest DB is Dark Matter !!

Cosmology - Darko-Baryo-Genesis

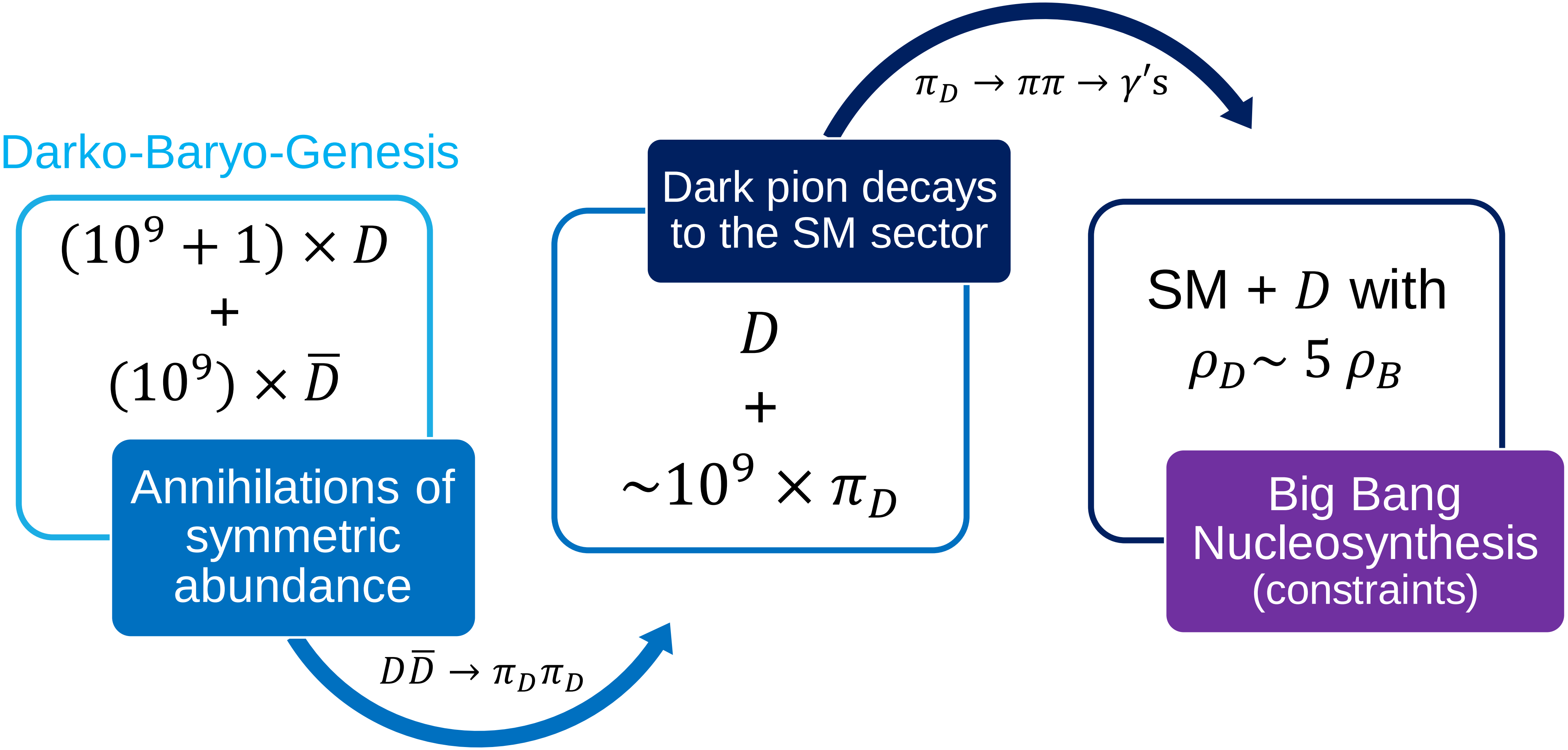
- The three Sakharov conditions must be satisfied for the generation of matter-antimatter asymmetries, including

1. Dark baryon number $U(1)_D$ and baryon number $U(1)_B$ violation
2. Charge conjugation (C) and charge conjugation parity (CP) violation
3. Out of thermal equilibrium process



1. With a new scalar Φ, we can introduce a decay which violate both $U(1)_D$ and $U(1)_B$ but preserve $U(1)_{B-D}$ $\Rightarrow$ $n_D = n_B$
2. With three generations of dark quarks, we can introduce new CP phases to accommodate the required asymmetry
3. Need $\Gamma < H \,@\, T = M_\Phi$ for the decay to be out of equilibrium

Cosmology – From DBG to BBN



Darko-Baryo-Genesis

$(10^9+1)\times D$

$+$

$(10^9)\times \bar{D}$

Annihilations of symmetric abundance

$D\bar{D}\to\pi_D\pi_D$

Dark pion decays to the SM sector

D

$+$

$\sim 10^9\times\pi_D$

$\pi_D\to\pi\pi\to\gamma's$

SM + D with

$\rho_D\sim 5\,\rho_B$

Big Bang Nucleosynthesis (constraints)

Signatures and Constraints

- Stability of Dark Matter

$$\Sigma \rightarrow n + \pi \quad \text{with constraint on the lifetime: } \tau_\Sigma > 10^{24} \sim 10^{28}\, s$$

- Dark Matter self-interaction

$$\sigma_D < \sigma_B \quad \Rightarrow \quad m_{\pi_D} > 60\ \text{GeV} \quad \Rightarrow \quad m_\chi > 0.3\ \text{MeV}$$

- Formation of Dark Matter Nuggets?
- Phase transition and gravitational waves?
- Collider signatures?
- Flavor observables?
- More to be studied～

Summary

- **Motivation**
  - The Dark Matter-Baryon Coincidence is a nontrivial condition
  - The coincidence might be the hint to probe the nature of Dark Matter
- **Model Building**
  - Similarity-based solutions implies Dark Sector ~ QCD Sector with Asymmetric Dark Baryon
  - Dark sector is composed of $Sp(4)_D$ with $3 \times (\chi_A + \chi_F)$ (Flavorful !!)
  - Dark GUT $SU(9)$ can unify SM $SU(5)$ + Dark Color $Sp(4)_D$ and explain the coincidence
- **Future prospect**
  - Concrete setup for scalar sector and dark fermion masses
  - Detailed cosmology and parameter space to be explored
  - Signatures and constraints from astronomy and phenomenology to be studied

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